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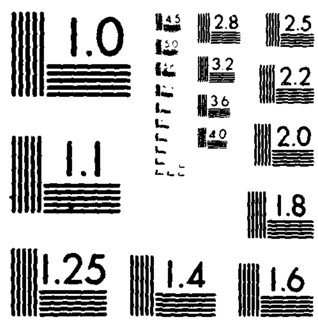

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Available mathematical models for peak blast wave overpressure at large distances from TNT explosions are surveyed. Analytical and empirical models are discussed.

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FOREWORD

This report was prepared as part of a development program to determine methods of reducing noise levels due to military weapons during testing and training operations. Early work was funded by the Naval Science Assistance Program (NSAP) at the request of COMTHIRDFLT and by the Navy Independent Research program. Major funding was provided under the Gun Blast Effects program, NAVSEATASK 653/497/004-1-S0956.

This report has been reviewed and approved by F. H. Maillie and J. F. Horton of the Systems Safety Division of the Combat Systems Department.

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A

CONTENTS

INTRODUCTION

A number of models and data sets exist for far-field* peak overpressure (peak sound pressure) due to explosive charges. The basic form of the model for far-field overpressure is based on similitude theory. A set of similarity parameters known as Sachs' scaling[1] describes the effects of distance, charge weight, and propagation medium properties (characterized by atmospheric pressure and sound speed) on blast wave parameters such as pressure, impulse, and time. For peak overpressure, the parametric relationship can be stated as

$$\frac{P_M}{P_a} = f\left(\frac{R\, P_a^{1/3}}{W^{1/3}}\right) \tag{1}$$

where

P_M = overpressure

P_a = absolute atmospheric pressure

R = distance

W = energy released by detonation of the explosive charge, usually expressed as weight of a standard explosive.

This model is commonly used to describe the effects of altitude on blast wave parameters. A special case of Sachs' scaling, for invariant ambient conditions, is known as Hopkinson scaling, the parametric relationship for peak overpressure being

$$P_M = f\left(\frac{R}{W^{1/3}}\right)$$

---

* The blast wave overpressure field is loosely divided into two zones, the near field and the far field, based on required mathematical models. In the far field, the linear, or acoustic, equations are adequate while in the near field, nonlinear shock wave theory is required for correct phenomenological description.

The functional form usually chosen is

$$P_M = C\ \lambda^{-\alpha} = C \left(\frac{R}{W^{1/3}} \right)^{-\alpha} \tag{2}$$

where

$$\lambda = R/W^{1/3} = \text{scaled distance.}$$

This is the most commonly used model for explosive blast wave peak overpressure. The parameters C and α are essentially constant in the far field (but not in the near field). The peak overpressure may be expressed as peak sound pressure level, in units of decibels, according to Equation (1),

$$L_{Pk} = 10\ \log_{10} \left(\frac{P_M}{P_o} \right)^2 = 20\ \log_{10} \left(\frac{P_M}{P_o} \right)$$

where $P_o = 20\ \mu P_a = 2.9 \times 10^{9}$ psi = zero reference for the decibel scale.

The effect of changes in propagation medium properties, such as those associated with changes in altitude in the atmosphere, may be determined by using the functional form of Equation (2) for the similarity parameters of Equation (1), i.e.,

$$\frac{P_M}{P_a} = C' \left(\frac{R\ P_a^{\ 1/3}}{W^{1/3}} \right)^{-\alpha}$$

For two different altitudes denoted by subscripts 1 and 2, with equal values of R and W, peak overpressures satisfy

$$\frac{P_{M,1}}{P_{M,2}} = \left(\frac{P_{a,1}}{P_{a,2}} \right)^{1-\frac{\alpha}{3}}$$

and the change in PSPL (peak sound pressure level) due to the change in atmospheric pressure is

$$\Delta PSPL = 20 \left(1 - \frac{\alpha}{3} \right) \log_{10} \left(\frac{P_{a,1}}{P_{a,2}} \right) \tag{3}$$

Note that this change is independent of the magnitude of R or W.

SURVEY OF AVAILABLE MODELS

Available models can be divided into two rather distinct types. One type of model is based on analytical calculations for a spherical blast wave propagating through a uniform infinite atmosphere ("free air"). The other is based on empirical data and implicitly includes the effects of propagation through the real atmosphere and reflection and ground attenuation effects.

The NOL model[2] is typical of the analytically based models. Calculations were carried out for three cases: a nuclear blast wave in ideal air, a nuclear blast wave in "real" air, in the one-dimensional calculations, and a TNT blast wave in "real" air ("real" air means that real gas attenuation effects were included in the one-dimensional calculations). All calculations were carried out for sea level "free-air" (uniform propagation medium of infinite volume, 15°C, 1 atm pressure) expansion of a spherical shock front and, thus, do not include atmospheric refraction effects or reflection and ground attenuation effects. An interesting result was that, below 1 psi, 1 kiloton nuclear was equivalent (on the basis of peak overpressure) to 0.7 kiloton TNT, rather than the well-known value of 0.5 which is applicable in the 5 to 50 psi range.

The NOL calculations for TNT were carried out for an overpressure range from 7,600 psi (248 dB) to 0.0001639 psi (95 dB); i.e., for both the near field and far field. The demarcation between near field and far field is somewhat arbitrary, but appears to be approximately 0.2 psi (156.8 dB), at which point the decay rate [the exponent α in Equation (1)] becomes constant; i.e., PSPL versus log R becomes linear.

A least-squares curve fit (squared multiple correlation coefficient = 0.999, agreement within 0.5 dB) of results of the NOL free-air TNT calculations, for $P < 0.2$ psi, yielded

$$P_M = 36.8\,\lambda^{-1.09} = 36.8\left(\frac{R}{W^{1/3}}\right)^{-1.09} \tag{4}$$

$$130 < \lambda \left(\frac{ft}{lb^{1/3}}\right) < 84{,}000$$

$$\text{units} \begin{cases} P_M & \text{psi} \\ R & \text{ft} \\ W & \text{lbs TNT} \end{cases}$$

or, in metric units

$$P_M = 49.7 \ \lambda^{-1.09} = 49.7 \left(\frac{R}{W^{1/3}}\right)^{-1.09} \tag{4a}$$

$$0.05 < \lambda \left(\frac{km}{kg^{1/3}}\right) < 33$$

$$\text{units} \begin{cases} P_M & \text{pascals} \\ R & \text{kilometers} \\ W & \text{kilograms TNT} \end{cases}$$

This model and other models discussed below are presented graphically in Figure 1.

The NOL results for nuclear explosions agree very well with other similar studies.[3,4] These nuclear models have been used as the basis for TNT overpressure models. Reed[5] recommends

$$P_M = 70.944 \ \lambda^{-1.1} = 70.944 \left(\frac{R}{W^{1/3}}\right)^{-1.1} \tag{5}$$

$$\text{units} \begin{cases} P_M & \text{pascals} \\ R & \text{kilometers} \\ W & \text{kilograms TNT} \end{cases}$$

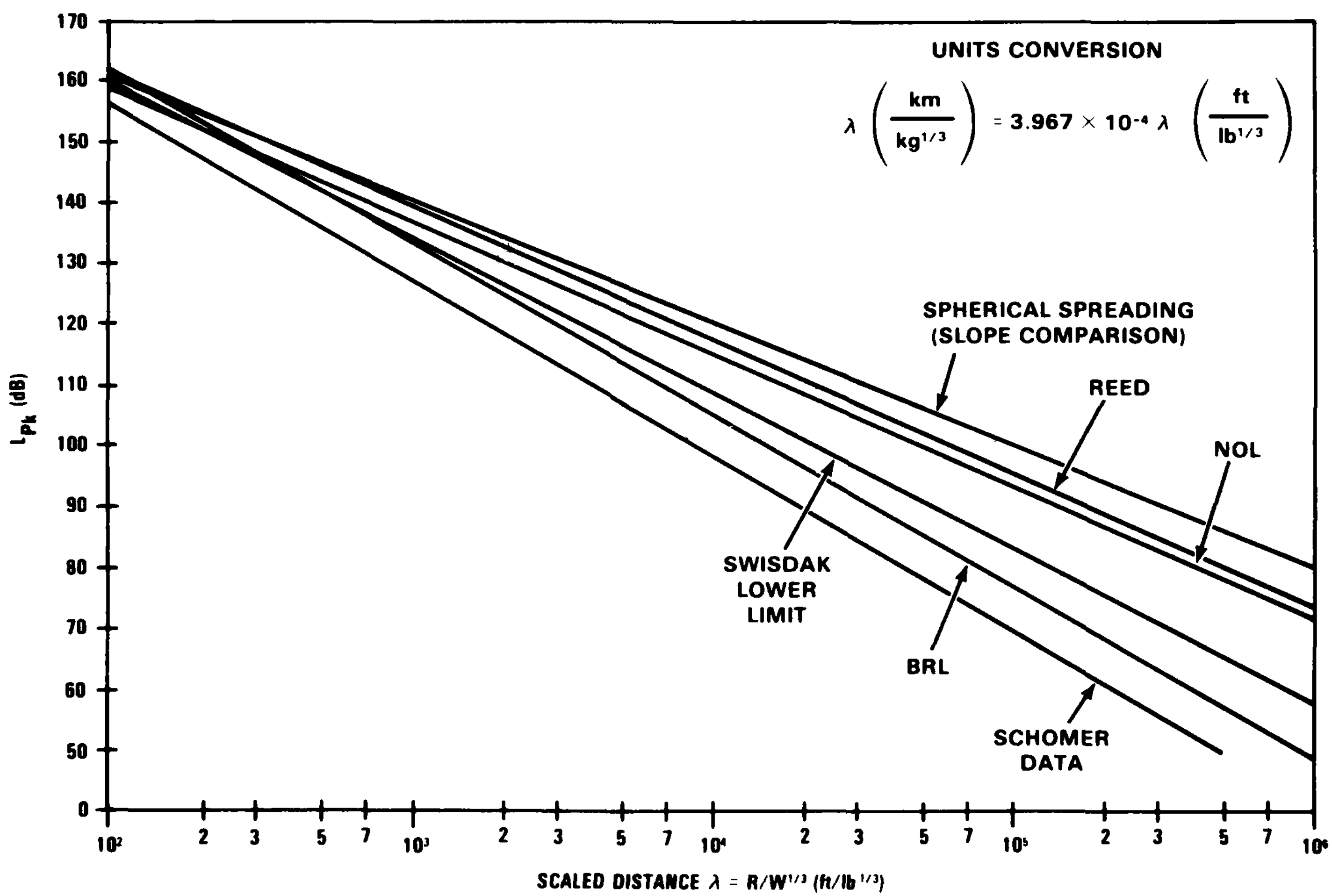

Figure 1. TNT Far-Field Peak Overpressure Models

or, in English units,

$$P_M = 56.8\ \lambda^{-1.1} = 56.8 \left(\frac{R}{W^{1/3}}\right)^{-1.1} \tag{5a}$$

$$\text{units} \begin{cases} P_M & \text{psi} \\ R & \text{ft} \\ W & \text{lbs TNT} \end{cases}$$

This model was extrapolated from the AFWL[3] free-air nuclear model using 0.5 kiloton TNT = 1 kiloton nuclear and by doubling the overpressure to account for surface burst versus spherical expansion. This model yields somewhat higher pressure levels than the NOL model, as could be expected in view of the NOL results for TNT-nuclear equivalency at low overpressures and because of Reed's correction for surface effects.

Swisdak[6] presents, in a graphical form, a band of predicted TNT far-field overpressures versus scaled distance for $10 < \lambda\ (\mathrm{ft/lb}^{1/3}) < 10{,}000$. The upper limit of this band essentially agrees with the NOL model [Equation (4)], while the lower limit of the band can be represented by

$$P_M = 108\ \lambda^{-1.28} = 108 \left(\frac{R}{W^{1/3}}\right)^{-1.28} \tag{6}$$

$$10 < \lambda \left(\frac{\mathrm{ft}}{16^{1/3}}\right) < 10{,}000$$

$$\text{units} \begin{cases} P_M & \text{psi} \\ R & \text{ft} \\ W & \text{lbs TNT} \end{cases}$$

or, in metric units,

$$P_M = 33.0 \ \lambda^{-1.28} = 33.0 \left(\frac{R}{W^{1/3}}\right)^{-1.28} \qquad (6a)$$

$$0.004 < \lambda \left(\frac{\mathrm{km}}{\mathrm{kg}^{1/3}}\right) < 4$$

$$\text{units} \begin{cases} P_M & \text{pascals} \\ R & \text{kilometers} \\ W & \text{kg TNT} \end{cases}$$

Swisdak[6] also presents near-field TNT blast wave parameters based on a survey of available experimental data. Swisdak's curve for near-field peak overpressure, shown in Figure 2, is a best fit of experimental TNT peak overpressure data (total data scatter ~10 to 15 percent).[7] Also shown in Figure 2 is the NOL[2] analytical TNT curve. The agreement is very good with a maximum disagreement of about 1 dB (~10%) at $\lambda = 66$ ft/lb$^{1/3}$. This good agreement between calculated and measured near-field results provides increased confidence that the NOL far-field results are valid.

For free-air spherical expansion without attenuation, overpressure is inversely proportional to distance; i.e., $\alpha = 1.0$ in Equation (2). This is shown in Figure 1, for comparison of slope (decay rate) only, and was arbitrarily located to pass through 158.5 dB at $\lambda = 100$ ft/lb$^{1/3}$. This spherical spreading decay rate amounts to -6 dB per doubling of distance or -20 dB per x 10 distance.

The BRL model[8] is an empirical model based on a total of 273 overpressure measurements made under undocumented, but presumably widely varying, atmospheric conditions. The atmospheric conditions were probably generally "negative gradient" conditions; i.e., sound speed monotonically decreasing with increasing altitude, which is characteristic of the "normal" or "average" atmospheric structure. This atmospheric structure refracts acoustic energy into the upper atmosphere, resulting in lower overpressure at the earth's surface than would be

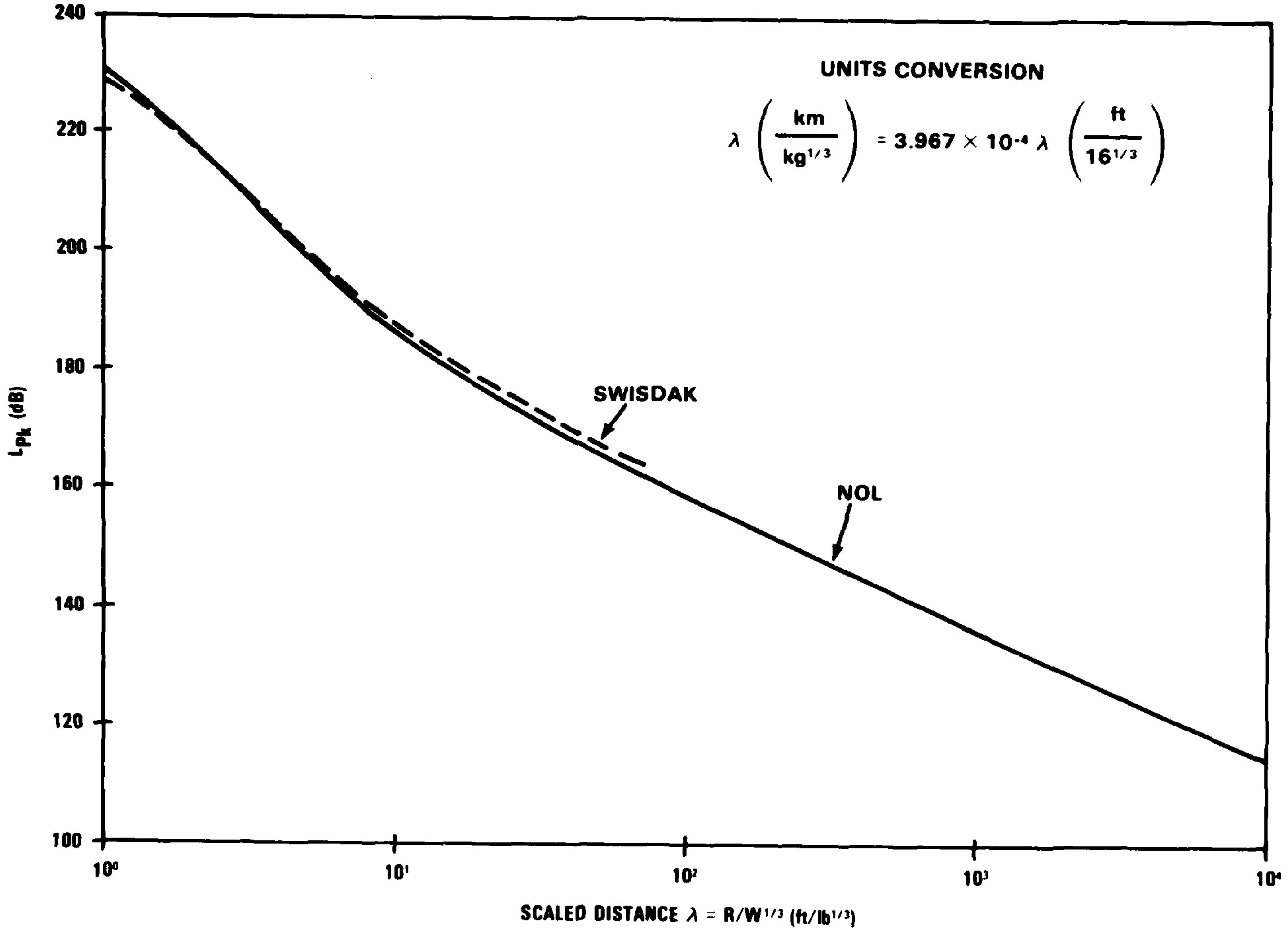

Figure 2. Comparison of NOL and Swisdak Near-Field TNT Free-Air Models

obtained for the uniform atmosphere assumed in the theoretical models. It should be noted that the empirical data also implicitly contains reflection and ground attenuation effects. The explosive events were surface bursts of roughly hemispherical TNT charges of 5, 20, and 100 tons. The data were processed to obtain the following low pressure range (P_M < 0.2 psi) model (constants rounded to three significant figures):

$$P_M = 227 \ \lambda^{-1.41} = 227 \left(\frac{R}{W^{1/3}}\right)^{-1.41} \tag{7}$$

$$40 < \lambda < 1000$$

$$\text{units} \begin{cases} P_M & \text{psi} \\ R & \text{ft} \\ W & \text{lbs TNT} \end{cases}$$

or, in metric units,

$$P_M = 25.0 \ \lambda^{-1.41} = 25.0 \left(\frac{R}{W^{1/3}}\right)^{-1.41} \tag{7a}$$

$$0.02 < \lambda < 0.4$$

$$\text{units} \begin{cases} P_M & \text{pascals} \\ R & \text{kilometers} \\ W & \text{kg TNT} \end{cases}$$

Equation (7) is often used outside of the parameter range stipulated, e.g., at scaled distances perhaps as large as 10^6 ft/lb$^{1/3}$. There is obviously some uncertainty as to the validity of the expression for small charges and large distances.

Recent data obtained by Schomer[9,10] provide useful information regarding the mean expected PSPL at very large distances from small explosive charges. Blast wave parameters were measured and recorded for 735 noise events, each due to surface burst detonation of a roughly hemispherical 5-lb (2.27-kg) C4 explosive charge. Atmospheric temperature gradient conditions ranged from surface inversion

to negative gradient. Measurements were made at 16 locations at distances of 2, 5, 10, and 15 miles in each of the four principal compass directions. One of the parameters measured was PSPL. Results of a statistical analysis of this PSPL data are shown in Table 1. The PSPL data, for each individual station as well as combined data for each distance, were examined for conformance with Gaussian distribution. PSPL population frequency distribution plots appeared to visual inspection to be roughly Gaussian for some (but not all) stations, but formal standard tests such as the "chi-squared" test indicated rather poor correlation. This means that the standard deviation (σ) values shown in Table 1, which are on the order of 10 dB, are of limited usefulness. One can conclude, however, that excursions of PSPL should lie within 10 dB of the mean expected value. For about two thirds of all noise events, excursions of more than about ±20 dB (2σ) from the mean PSPL value, for any given value of λ, should occur infrequently, and excursions of more than ±30 dB (3σ) should be rare. This observation agrees very well with measurement experience. The PSPL data were also converted to peak overpressure; the resulting frequency distribution plots were not even approximately Gaussian.

The data shown in Table 1 provide the basis for a refined far-field mean expected peak overpressure model for small charges and large scaled distances. First, the equivalent TNT charge weight for a 5-lb C4 charge must be determined. Swisdak[6] shows TNT equivalent charge weight ratio for C4, based on peak overpressure, to vary from ~1.45 at 100 psi to ~1.2 at 10 psi with no data presented for the very low pressures of interest in the current study. It seems reasonable to assume that the appropriate equivalency factor is probably less than 1.2, possibly ~1.0 (as past experience indicates). If the C4 peak overpressure equivalent TNT charge weight is between 0.8 and 1.2, using 1.0 results in an error in predicted PSPL of less than 0.75 dB. Thus, for far-field peak overpressure modeling, no distinction will be made between C4 and TNT. The data of Table 1 was obtained at Fort Leonard Wood, Missouri, about 1,000 ft (about 300 m) above sea level. Correction of the data to sea level conditions, by means of Equation (3), amounts to +0.3 dB. A least-squares curve fit of the mean PSPL

Table 1. Experimental C4 Far-Field PSPL Data

Station	L_{Pk}			
	N	Mean (dB)	σ (dB)	Extreme Values (dB)
2 Mile North	656	110.0	5.7	93.6 / 130.0
2 Mile East	712	110.8	6.5	90.6 / 132.2
2 Mile South	732	98.9	9.2	80.0 / 121.6
2 Mile West	697	100.6	8.2	80.5 / 124.0
2 Mile All	2797	105.0	9.3	80.0 / 132.2
5 Mile North	718	94.4	8.3	73.5 / 118.5
5 Mile East	687	99.9	8.3	70.5 / 120.4
5 Mile South	594	91.9	13.2	56.0 / 117.7
5 Mile West	675	81.6	8.7	63.0 / 117.5
5 Mile All	2674	92.0	11.8	56.0 / 120.4
10 Mile North	711	81.3	10.0	63.5 / 113.5
10 Mile East	701	89.0	10.4	67.8 / 116.3
10 Mile South	712	90.6	8.3	70.0 / 114.7
10 Mile West	700	79.0	7.4	65.5 / 112.0
10 Mile All	2824	85.0	10.4	63.5 / 116.3
15 Mile North	671	75.7	8.3	66.7 / 104.0
15 Mile East	701	80.8	8.2	66.2 / 104.0
15 Mile South	604	86.4	8.4	70.0 / 113.0
15 Mile West	613	75.0	7.8	70.0 / 105.0
15 Mile All	2589	79.4	9.3	66.2 / 113.0

data of Table 1, corrected to sea level, yielded (squared multiple correlation coefficient = 0.995):

$$P_M = 143\ \lambda^{-1.44} = 143\left(\frac{R}{W^{1/3}}\right)^{-1.44} \tag{8}$$

$$6{,}180 < \lambda\ (\mathrm{ft/lb}^{1/3}) < 46{,}300$$

$$\text{units}\ \begin{cases} P_M & \text{psi} \\ R & \text{ft} \\ W & \text{lbs TNT} \end{cases}$$

or, in metric units,

$$P_M = 12.4\ \lambda^{-1.44} = 12.4\left(\frac{R}{W^{1/3}}\right)^{-1.44} \tag{8a}$$

$$2.45 < \lambda < 18.4$$

$$\text{units}\ \begin{cases} P_M & \text{pascals} \\ R & \text{kilometers} \\ W & \text{kg TNT} \end{cases}$$

This model falls about 5 dB below the BRL model (see Figure 1). The fact that this model is based on a great deal of data, for small charges and large distances, provides considerable confidence in the validity of the model.

CLOSURE

Either a "free-air" or a "mean expected" blast overpressure model could be used to predict far-field blast noise levels. A "free-air" model has the advantages of being a well-defined baseline propagation condition (i.e., a uniform quiescent propagation medium of known property values); however, such a propagation condition does not, in general, occur in nature. A "mean expected level"

model, based on empirical data obtained under a wide variety of atmospheric condition, yields a better indication of noise levels that would actually be encountered in practice. A disadvantage of such a model is that the atmospheric structure that yields the "mean expected level," and the correlation between atmospheric structure and resultant noise level, is not well defined. Also, it is not necessarily clear that the "mean expected level" is the same for different geographic locations and terrain characteristics. Thus, a "mean expected level" model yields only approximate, though quite realistic, predictions of blast wave overpressure levels.

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